Titanium Investment Casting Defects: A Metallographic Overview

J.D. Cotton, L.P. Clark, and H.R. Phelps

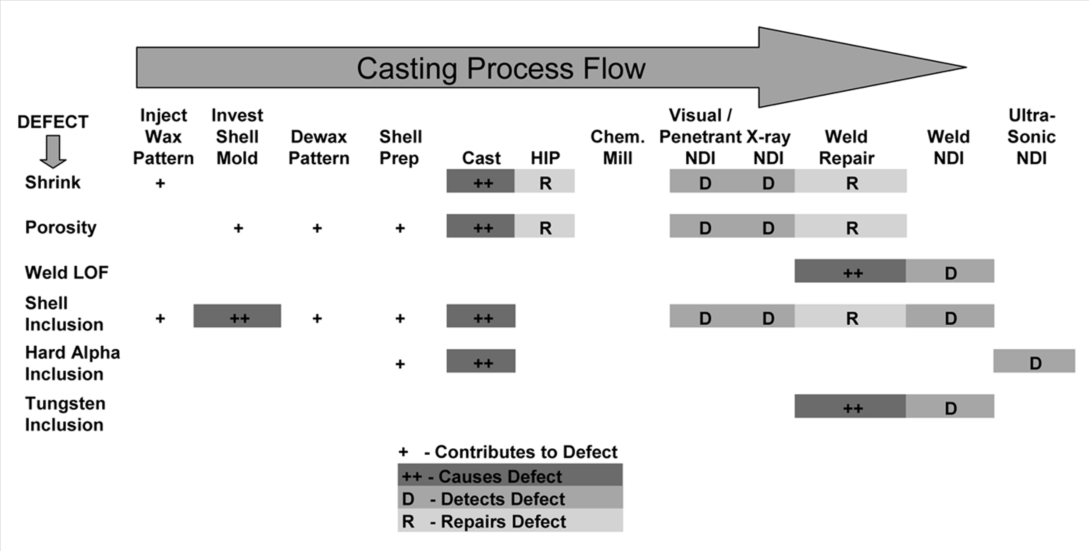
Although titanium castings have been used in aerospace structures for decades, those uses have largely been in secondary applications. Expanding the use of titanium castings in critical applications would be encouraged by a better understanding of investment casting defects in titanium alloy systems. This paper describes several types of casting-related defects that are identified as potentially affecting the design life of a structure: inclusions, voids, and weld repair defects.

INTRODUCTION

Titanium castings have been used in aerospace structures for nearly 40 years, but historically were limited to secondary, or noncritical, structural applications.[1–3] In recent decades, their extensive use in turbojet engine components, especially frames and blades, has built confidence in the quality and consistency of this titanium product form, and today they are used in a number of primary airframe applications.[4–6] Despite this growth, very little has been published regarding the nature of investment casting defects for titanium alloy systems. Continued expansion of titanium casting use in critical applications would be encouraged by a better understanding of defects in this product form. This information can support, for example, durability and damage tolerance life analyses,[7] and essential quality improvement. Several types of casting-related defects are identified as potentially affecting the design life of a structure: inclusions, voids, and weld repair defects.[8,9] These are briefly described in this paper in terms of type, control, and microstructure.

TITANIUM INVESTMENT CASTING PROCESS

The first titanium castings were produced in 1954 by the U.S. Bureau of Mines using machined graphite molds.[10] The lost-wax investment molding process, currently the principal technology for aerospace castings, was introduced in the mid-1960s[1] and has come to be the predominant casting process for titanium (titanium is too reactive for conventional sand-casting methods). In the lost-wax process, a wax pattern of the part is produced by injection molding in hard dies. Once the wax pattern, sprues, runners, gates, and risers are joined, the wax pattern assembly is then coated with a vendor-proprietary ceramic face coat. The primary characteristics of the face coats are low reactivity and the ability to withstand the thermal shock from contact with molten titanium. The more reactive the face coat, the thicker the reaction layer (known as alpha case) that will form on the metal surface. After the face coat, successive layers of ceramic stucco and slurries are applied until the mold has the required strength and rigidity for subsequent processing. Each ceramic layer is allowed to dry and cure under controlled temperature and humidity conditions. Once the ceramic



DEFECT	Inject Wax Pattern	Invest Shell Mold	Dewax Pattern	Shell Prep	Cast	HIP	Chem. Mill	Visual / Penetrant NDI	X-ray NDI	Weld Repair	Weld NDI	Ultra-Sonic NDI
Shrink	+				++	R		D	D	R		
Porosity		+	+	+	++	R		D	D	R		
Weld LOF										++	D	
Shell Inclusion	+	++	+	+	++			D	D	R	D	
Hard Alpha Inclusion				+	++							D
Tungsten Inclusion										++	D	

+ - Contributes to Defect
++ - Causes Defect
D - Detects Defect
R - Repairs Defect

Figure 1. Titanium casting defects versus process flow.[13]

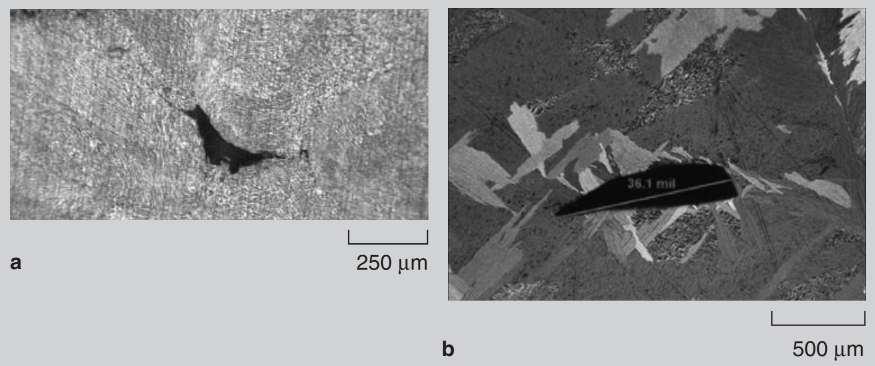


Figure 2. Light-optical photomicrographs of void-type flaws in titanium investment castings. (a) Partially closed shrink void and (b) weld lack-of-fusion void.

mold build operations are completed, the wax pattern is melted out in a hydroclave. The ceramic mold is then fired to develop full strength and combust any organic residues prior to casting.[11]

During the casting process, molten titanium is poured into the mold under vacuum and allowed to solidify. On extraction from the furnace and cooling, the ceramic shell material, sprues, gates, and risers are removed prior to hot-isostatic pressing (HIP) processing. The HIP process subjects the casting to elevated temperature and isostatic gas pressure, typically 900°C and 103 MPa pressure for 2 h for the Ti6Al4V alloy.[12] The intent of the HIP process is to eliminate internal void defects by collapse and diffusion bonding.[4]

After HIP, the castings are inspected to locate defects, as indicated by the "D"s in Figure 1. These include surface-connected voids (which HIP will not heal) and inclusions.[8,9] Larger castings (say larger than 11 kg) will typically have one or two rejectable internal flaws, while smaller castings often have none. On detection, the defects are removed by grinding and the area is weld repaired using gas-tungsten arc (GTA) methods. The majority of casting defects are located and repaired, but are, of course, subject to inspectability limits. Those that remain tend to be small and rare, and as such, have not been well characterized in the literature. The intent of this paper is to provide an introduction to titanium investment casting defects.

Such flaws may be simply classified into two types: voids and inclusions. Voids are the absence of solid material in the casting and include shrink porosity, gas pores, and weld lack-of-fusion (LOF) cavities. Inclusions constitute any undesirable exogenous material in the microstructure, and consist mainly of shell inclusions, hard alpha inclusions, and metallic tungsten inclusions. Ti6Al4V, which constitutes about 90% of titanium foundry production volume, is not prone to solidification defects (e.g., coring). Some examples of void and inclusion defects are presented in the following.

Voids

Voids may occur as shrink, gas, or weld LOF cavities in titanium investment castings. Shrink voids result from the reduction in volume as the molten metal solidifies and contracts. Such voids can be sizeable, on the order of 1–2 cm, but are usually closed and bonded by standard HIP processing.[14] Shrink void defects can be minimized by sound gating practices to insure a source of molten filler metal to move the shrink out of the part envelope, although the historical foundry approach has been to gate conservatively (reducing pour weight) and rely on HIP to close porosity. Gas pores can develop if gases (such as hydrogen) liberated by the solidifying metal, or from the mold wall, do not escape prior to passage of the solidification front. The entrapped gas forms bubbles in the casting. The authors' experience is that gas defects are relatively rare and small. Weld LOF cavities may develop during weld repair of the casting and so are not truly casting defects. However, they are generated during post-casting foundry processing and do contribute to the defect population. They are typically due to poor surface preparation or inadequate heat delivered in the weld pool—hence, repair locations with difficult access are more prone to LOF. Lack-of-fusion voids rarely exceed 2 mm in maximum dimension.

In rare instances, shrink or gas voids

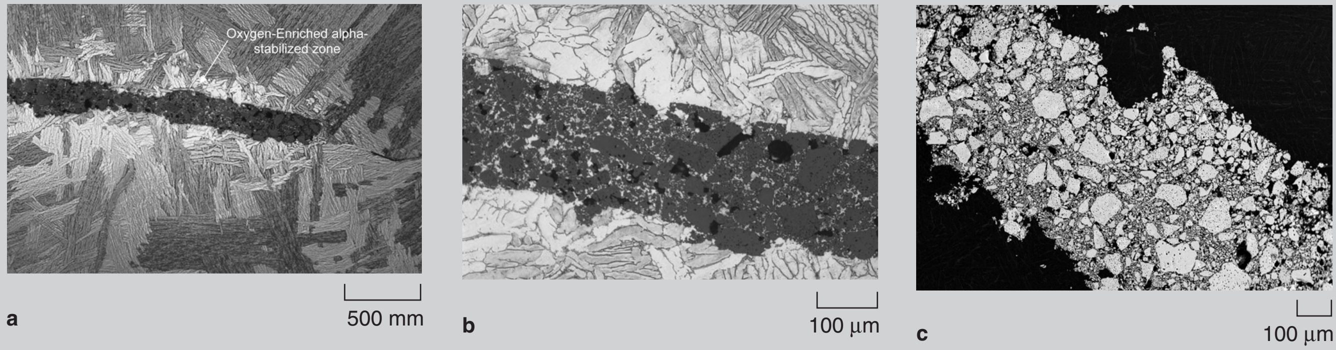


Figure 3. Photomicrographs of a cross-sectioned ceramic shell inclusion in a titanium investment casting. (a) Light optical; (b) higher-magnification light optical; (c) backscattered-electron image. Individual ceramic phases are visible.

persist after standard HIP processing. This may occur if an undetected gas path exists between the void and the surface (providing a route for pressure equalization during HIP and no net closure force), or if the geometry prevents adequate metal deformation. Lack-of-fusion voids have no opportunity for HIP closure since weld repairs occur after HIP processing. Post-HIP voids in titanium castings are irregular in geometry and may be associated with a recrystallized grain structure (due to deformation during HIP closure deformation). Metallographic examples of voids are shown in Figure 2.

Inclusions

Inclusions are defined here as exogenous solid defects in the casting and occur as three main types: ceramic shell, hard alpha, and tungsten. Ceramic shell inclusions originate in the ceramic mold due to spall from the inner mold layers or thin ceramic flash from open wax seals that detach. These inclusions usually contain proprietary mixtures of ceramic phases of a flake-like geometry that rarely exceeds 4 mm in maximum dimension. They are often surrounded by an oxygen-enriched reaction zone, typically 500 µm thick. This results from thermodynamic reduction of the oxide phases in the shell material by the molten titanium, interstitial oxygen liberation, and radial outward diffusion.[8] This diffusion zone etches lighter than the matrix, causes some α-Ti lamellae thickening, and hardens the matrix. Figures 3 and 4 show examples of shell inclusions in a Ti6Al4V casting in which these features are visible.

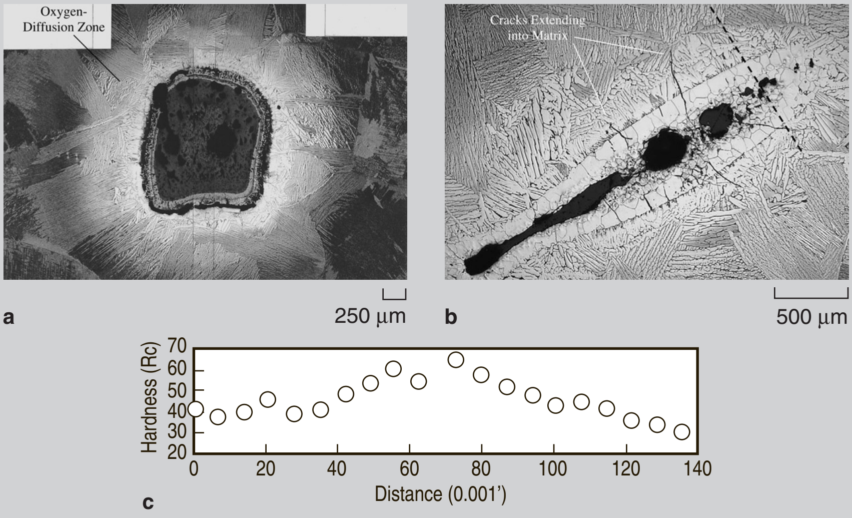


Figure 5. Metallographic cross-sections of hard alpha inclusions. These are suspected to have originated from (a) torch cutting debris and (b) weld splatter debris. (c) is a microhardness traverse across the dotted line in (b). The light-etching area surrounding each inclusion is due to oxygen diffusion from the core into the α–β matrix, similar to oxide ceramic inclusions above. Note the heavy porosity and cracking that extends to the limits of the diffusion zone.

Hard alpha inclusions are interstitially stabilized particles of alpha-rich titanium alloy inherited from melt stock defects, or formed during torch cutting, welding, or other operations that expose molten metal to the atmosphere.[8,13] Once produced by these peripheral operations, the contaminated debris can inadvertently enter the melt through a variety of transfer mechanisms.[8,15] The addition of nitrogen and/or oxygen causes the melting point of these defects to exceed that of the base alloy and, given the small superheat (less than 60°C) of the industry-standard vacuum-arc remelting process, they can survive the casting process. The small density difference between hard alpha phases and titanium alloy makes radiographic detection unreliable, although phased-array ultrasonic inspection[16] is capable of finding associated interfaces and internal porosity.[13] Foundry cleanliness and contamination controls have been found to be effective in significantly reducing the incidence of hard alpha defects in critical titanium castings.[8]

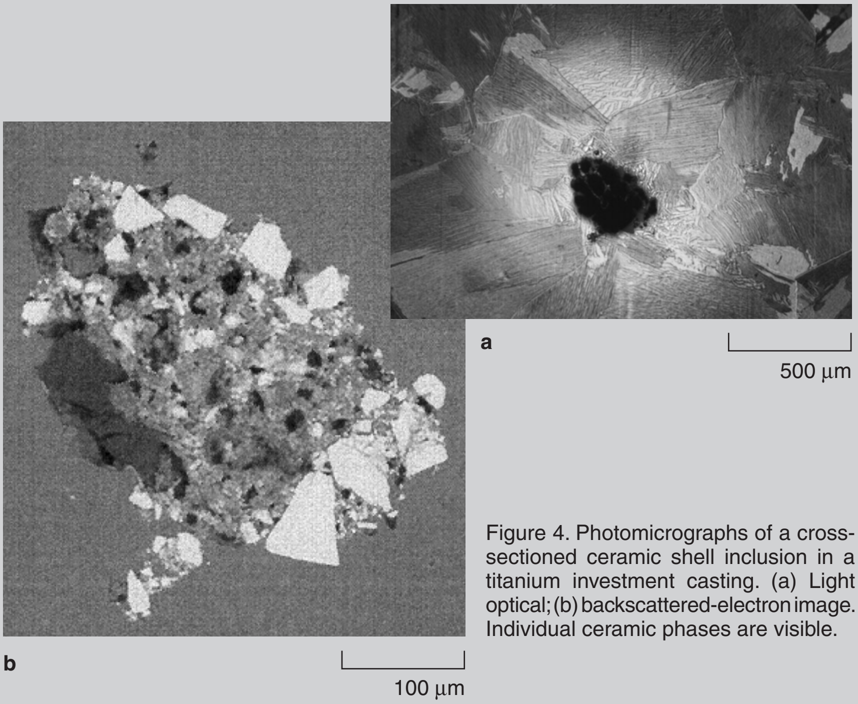


Figure 4. Photomicrographs of a cross-sectioned ceramic shell inclusion in a titanium investment casting. (a) Light optical; (b) backscattered-electron image. Individual ceramic phases are visible.

Metallographic cross sections of hard alpha inclusions are shown in Figure 5. They are typified by a core of Ti-O or Ti-N phases (often, with Ti$_3$Al) surrounded by porous, embrittled α-Ti phase. The surrounding α-Ti grain structure is equiaxed and rejects β-stabilizing elements (such as vanadium or molybdenum) into the matrix (Figure 5b). The matrix adjacent to the inclusion will generally contain elevated interstitial levels, causing the α laths to thicken and the etching contrast to be lighter. This "halo" zone is typically 500–1,000 µm in radial thickness. There is a measurable increase in hardness at the inclusion core that may approach HRC 70 (Figure 5c).

Tungsten inclusions (not shown) are mainly due to improper welding technique. They form by the accidental contact of the GTA welding tip to the melt pool, causing a small amount of tungsten to be deposited. In most cases, this is known to the welder and appropriate measures are taken to rework the area. If not, tungsten is highly detectable in x-ray inspection due to its high atomic number contrast relative to titanium, and it may be found, removed, and the area repaired. Tungsten is a β-stabilizing element in titanium but does not dissolve sufficiently during the typical welding cycle to cause microstructural changes in the matrix. Therefore, it tends to appear as a rounded, isolated globule of foreign, dark-etching material.

CONCLUSION

The defects discussed here are relatively rare because of well-established foundry processes. This results in a high-quality, economical product that is seeing increased use in critical applications.

ACKNOWLEDGEMENTS

The authors express appreciation to Rodney R. Boyer for his careful technical review of the manuscript and to the U.S. Air Force for funding under contract F33657-97-C-0031.

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